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# Matching Performance of Falling Film Generation Process

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**Abstract**

In this paper, the match properties have been discussed with a simplified heat and mass transfer model of generator. It is revealed that besides the heat and mass transfer coefficients, the inlet parameters (temperature, concentration, flow rate etc.) are also important for the design optimization. This paper discusses the best flow rate ratio of solution and required condition for inlet properties match. Though the model is quite simplified, the conclusions are important for the real projects operation and optimization.


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*Keywords:* Absorption Heat Pump; Generator; Heat and Mass Transfer

## 1. Introduction

Recently, absorption heat pumps (AHPs) have been applied in many occasions. This kind of heat pumps is driven by heat other than electricity, and can be applied in many occasions different from the conventional heat pumps, especially in the industry waste heat recovery field.

Therefore, more and more research on absorption heat pumps or absorption chillers came out in the recent decades. Among all the literatures, many focus on the applications and overall performance of different types of machines. For example, Alarcon-Padilla and Garcia-Rodriguez[1] discussed a double-effect absorption heat pump coupled with a distillation system, and figures out several advantages of applying an AHP here. Keil et al. [2] took three application examples in Southern Germany, and analyzed the energetic economic performance. Some other papers[3][4][5] also reported applications (design, tests or simulation) in other systems and regions.

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On the other hand, the heat and mass transfer properties are crucial for the AHPs, for both simulation and optimization. So there are also quite much research about the heat and mass transfer in the four components, the absorber, generator, evaporator and condenser, among which, discussion about the latter two components are more common, since studies about evaporators and condensers are sufficient in the compressive heat pump systems. Different types of experiments of absorbers and generators with different working fluids are conducted. Some are set to test the heat and mass transfer coefficients or other transfer properties[6][7][8][9][10], and some are set to observe the flow behavior[11][12]. Depending on the experimental fundamentals, some models are put forward, and researchers wish to compute the behavior inside numerically[8][13][14] or even analytically[15].

Further on, researchers want to improve the performance of AHPs, by exploring different working fluids, using the enhance surfaces[16], additives in solutions [17] and so on[18][19]. However, discussion about the design of operating parameters is very limited. An important part to improve the performance is overcome. The generators and absorbers can be seen as heat exchangers between water (or steam, etc.) and solution. For a heat exchanger without phase change, besides the heat transfer coefficient, the flowrate ratio of both sides also influences the heat transfer a lot. If the heat capacity of both side matches each other, the transfer area demanded is minimum with the same heat transfer capacity and same temperature grade provided. In the other words, the heat transfer capacity can reach the maximum with the same transfer area and same temperature grade provided. The problem is similar in an AHP. The flow rate, concentration and temperature level of solution inside an AHP machine would influence the heat and mass transfer properties quite much. Since the solution flow rate and concentration is variable in the design stage, it is important to figure out how these properties would influence the heat and mass transfer, besides the properties heat and mass transfer coefficients et al. So in this study, the match properties are discussed, under a simplified generator heat and mass transfer model.

**Nomenclature**

| | |
|---|---|
| c | thermal capacity |
| F | transfer area |
| h | enthalpy |
| k | heat transfer coefficient |
| ka | mass transfer coefficient |
| m | mass flow rate |
| p | pressure |
| Q | heat transfer rate |
| T | absolute temperature |
| t | centigrade temperature |
| x | mass fraction of LiBr |
| ρ | density |

## 2. Numerical Analysis

### *2.1. Model Description*

In this paper, generators with only evaporation are discussed. The generator is heated by hot water, and cooling water cools the condenser. While the solution flows down in the generator, it is heated by the hot water. Temperature of solution would increase, and as a result, the saturated vapor pressure increases, and the solution evaporates at the same time. As mentioned above, only the evaporation but no boiling is discussed here. So phase change only happens on the outer face of solution film, and the mass transfer inside the film. The previous experiments showed that this assumption is rational, since under many conditions, no boiling was observed.

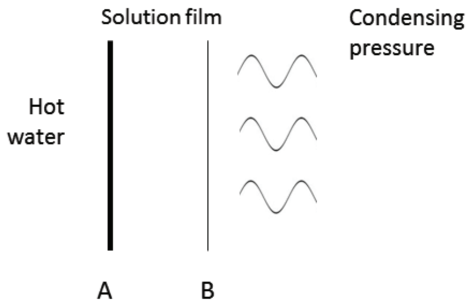



Fig. 1. Schematic of the generator model.

Thus, the model of generators is simplified as follows. The hot water either flows down or flows up along one side of the wall, and the solution flows down on the other. The heat from hot water is transferred to the inner face of solution film through boundary A. So the heat transfer capacity through A can be calculated:

$$dQ = k\Delta t dF \tag{1}$$

The temperature and concentration distribution in the direction perpendicular to flowing direction is ignored. So the model is just one-dimensional. And the phase change happens on the boundary B. So the mass transfer capacity is calculated through the equation:

$$dm = k_a \rho \Delta x dF \tag{2}$$

In these equations, k and ka represents the heat and mass transfer coefficients respectively. F is area for heat and mass transfer, and ρ is the density of the bulk solution. Solution on boundary B comes into direct contact with the vapor, the pressure of which is equal to the condensing pressure. The surfaces of the solution columns are considered to be saturated, i.e., the saturated vapor pressure is also equal to the condensing pressure. As a result, there exists a difference between the surface and bulk concentration, which is the driving force of the mass transfer. And this concentration difference is denoted as Δx in equation (2).

We can also get the energy and mass equation as follows:

$$dQ + d(mh)l = hevapdm \tag{3}$$

$$xm = const \tag{4}$$

*2.2. Problem description*

For many literatures, the heat and mass transfer performance of a generator is discussed. However, besides the heat and mass transfer coefficients, there are many other factors that can determine the performance of a generator-condenser. And there are two important problems to be discussed. First is how to define the “good performance” of a generator. Literatures used many indexes to judge the performance of a whole absorption chiller, among which COP is the most popular one. But for the single part of generator, there is no such an index. And the second is how to realize the good performance of a generator. In this paper, these two questions are discussed based on the simplified model mentioned above.

Different criteria have been put forward to judge different aspects of an absorption heat pump. For example, the COP (coefficient of performance) is the ratio of heat capacity input (heat source) and cold capacity output. Usually, the higher COP is better, for it means less pay and more gain.

The function of a generator in an absorption heat pump is to generate solution with the help of hot water at a low vapor pressure maintained by the cooling water in the condenser. So the input of a generator is the heat from hot water, and the output is the concentrated solution. For a good generator, it is expected to require the temperature of hot water as low as possible, when the concentration of solution are determined (circulating between the generator and the absorber), as well as the condensing pressure, and the outlet concentration. That is to produce certain amount of concentrated solution with the hot water of lowest temperature.

### *2.3. Examples and discussion*

The discussion is based on the simplified model. And the heat and mass transfer coefficients are set to be constant through the calculation, to discuss the influence of some other factors other than the heat and mass transfer performance.

On the other hand, the solution is circulated between the generator and absorber, and the inlet concentration in generator is determined during the installation, and cannot be easily changed. So the inlet concentration is constant in this problem. And so is the solution flow rate.

Thus, the question discussed here is, what the lowest temperature of hot water is, for a generator with determined inlet solution concentration, transfer area and heat and mass transfer coefficients, condensing pressure, and the amount of vaporized water.

Table 1. Preset value for calculation

| | Default value | unit |
|---|---|---|
| heat transfer coefficient<br>k | 1404 | W/(m2K) |
| Mass transfer coefficient<br>Ka | 5.52*10-4 | m/s |
| Mass transfer area<br>F | 1 | m2 |
| Inlet mass flow rate of solution<br>M | 0.1 | kg/s |
| Inlet concentration<br>xin | 54 | % |
| Outlet concentration<br>xout | 55 | % |
| Condensing pressure | 3 | kPa |

The preset values in these calculation examples are listed in Tab.1. The heat and mass transfer coefficients are consistent with the experimental results.

#### *2.3.1 Ideal cases*

As the solution is evaporated in the generator, the saturated vapor pressure of solution is not lower than the condensing pressure. If the solution can stay saturated during evaporation, the temperature of solution is lowest. Under this condition, the state of solution (temperature as well as concentration) is determined and temperature of the solution is lower than any other possible conditions, which is shown in fig 2. The line shows the lowest temperature solution can reach.

On the other hand, the heat transfer area is also infinite. So if the heat capacity of hot water is the same with solution equivalent heat capacity, then the temperature change of hot water can be totally the same with solution. Then the dash line in figure 2 is also the lowest possible temperature of the hot water, Because of the resistance of mass transfer, temperature of solution in real conditions would be higher than the solid line. Additionally, because of the heat transfer resistance, the temperature of hot water in real conditions should be higher than the solution temperature, i.e.:

$$T_w \geq T_s \geq T_{sat} \tag{5}$$

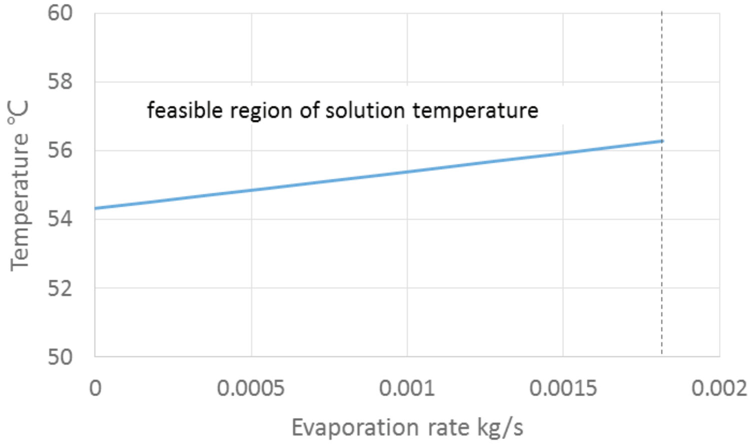



Fig. 2. Feasible region of solution temperature

Even with the infinite transfer area, the temperature of hot water cannot be as low as that of saturated solution in the ideal conditions unless the heat capacity of hot water equals to that of the saturated solution, which is similar with a heat exchanger.

$$dQ = c_{pe} m_s dt \tag{6}$$

$$dQ = (m_s - dm)h(x + dx, t + dt) + h_{vapor} dm - m_s h(x, t) \tag{7}$$

According to the mass equation,

$$dm = m_s \left(1 - \frac{x}{x + dx}\right) \tag{8}$$

So the equivalent thermal capacity equals to,

$$c_{pe} = \frac{x}{x + dx} \frac{h(x + dx, t + dt)}{dt} + \frac{dx}{x + dx} \frac{h_{vapor}}{dt} - \frac{h(x, t)}{dt} = c_p + x_t^{'} \left( \frac{\partial h}{\partial x} + \frac{h_{vapor} - h(x, t)}{x} \right) \tag{9}$$

It can be inferred that, the equivalent thermal capacity cpe is determined by the state parameter of solution, and the evaporation path of solution, which can be described by f(x,t)=0.

In the ideal conditions, the solution stays saturated while evaporating, so

$$P_{LiBr-H_2O}(x, t) = const \tag{10}$$

Thus, the equivalent thermal capacity can be calculated.

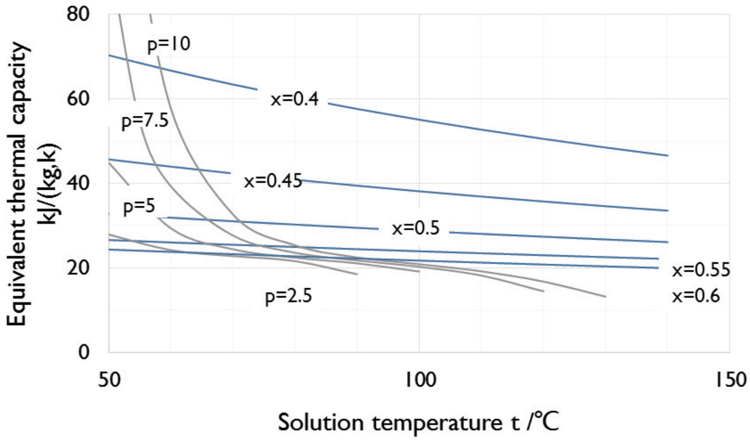


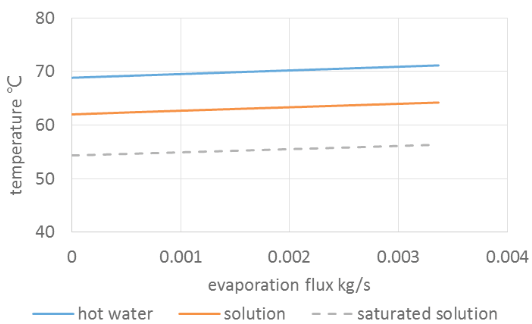

Fig. 3. Equivalent thermal capacity of LiBr-H2O solution

The results are shown in Fig.3. It can be inferred that when the saturated vapor pressure remains the same, the equivalent thermal capacity may change as the solution evaporates and gets concentrated. Under the ideal conditions, solution is expected to keep saturated, i.e. the saturated pressure keeps the same with condensing pressure. Then thermal capacity of hot water cannot be precisely the same with solution. However, in a real generator, the concentration change is usually as small as 1%, and the thermal capacity difference due to concentration and temperature changes can be ignored.

### 2.3.2 Real cases

While in the real cases, the transfer area cannot be infinite. Then the temperature differences exist. So the temperature of solution and hot water would satisfy the inequality: $T_w > T_s > T_{sat}$ .

In the ideal cases, temperature of hot water and solution can both be as low as the dash line, which cannot be realized in real cases. However, the flow rate match conditions still work here. If the flow rate of hot water is smaller, then the inlet temperature of hot water needed to be higher, for the same amount of evaporation, as shown in fig. 4.



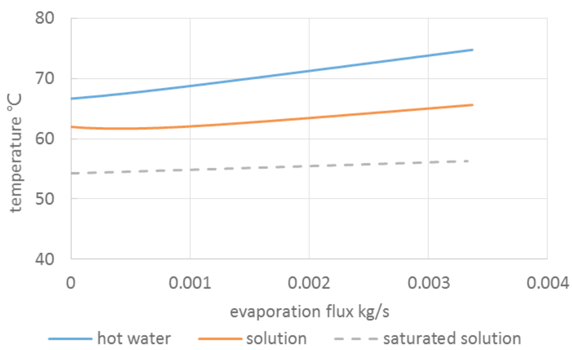
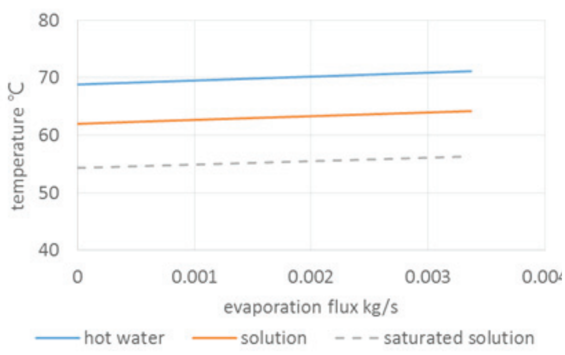



Fig. 4. Temperature change of solution and hot water: (a) mw=1kg/s; (b) mw=0.3 kg/s

One example is shown in fig.5. The blue line stands for the temperature of hot water, and the red line is the temperature of solution. The dash line stands for the temperature of saturated solution, which is the lowest temperature that solution can reach theoretically. The flow rate of hot water and the solution matches with each other, so the temperature curve are approximately parallel in fig.5(a).



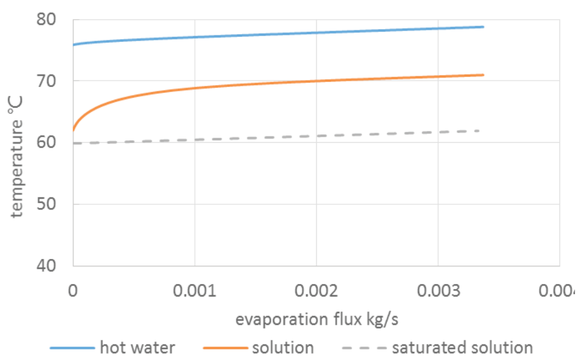




Fig. 5. Temperature change of solution and hot water: (a) Ps=3 kPa; (b) Ps=4 kPa

In real cases, even if the flow rate ratio of hot water and solution is proper to fit the flow rate conditions mentioned previously, the solution will only evaporates in the way expected when the heat and mass transfer rates are proper:

$$kdF(t_{w\_out} - t_{s\_in}) = c_{pe} m_s dt \tag{11}$$

$$k_a \rho dF(x - x_s) = dm = m_s \frac{dx}{x + dx} \tag{12}$$

That is to say, at the inlet point of solution, the temperature difference between hot water and solution, as well as the concentration difference between the bulk solution and the saturated solution should satisfy the equation written below.

$$\frac{k(t_{w\_out} - t_{s\_in})}{k_a \rho (x - x_s)} = c_{pe} \frac{x}{x_t^{'}} \tag{13}$$

If the heat transfer is fast, or the mass transfer is slow, temperature increases while the evaporation is not enough. As a result, the vapor pressure of solution will get higher. Then in the initial stage, the solution and hot water flows do no match with each other, as the case shown in fig. 5(b). All the other conditions are the same in fig. 5(a) and 5(b), except that the condensing pressure in the second condition is 1kPa higher. This is the inlet properties match problem, which does not exist in the ideal conditions.

## 3. DISCUSSIONS

In this paper, the match properties have been discussed with a simplified heat and mass transfer model of generator. It is revealed that besides the heat and mass transfer coefficients, the inlet parameters (temperature, concentration, flow rate etc.) are also important for the design optimization. This paper discusses the best flow rate ratio of solution and required condition for inlet properties match. Though the model is quite simplified, the conclusions are important for the real projects operation and optimization.

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